

HIGHLY COHERENT KILOHERTZ QUASI-PERIODIC OSCILLATIONS FROM A NEUTRON STAR X-RAY BINARY EXO 1745–248

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ABSTRACT

We report the discovery (20σ) of kilohertz quasi-periodic oscillations (kHz QPOs) at ~ 690 Hz from the transient neutron star low-mass X-ray binary EXO 1745–248. We find that this is a lower kHz QPO, and systematically study the time variation of its properties using smaller data segments with and without the shift-and-add technique. The quality (Q) factor occasionally significantly varies within short ranges of frequency and time. A high Q-factor (264.5 ± 38.5) of the QPO is found for a 200 s time segment, which might be the largest value reported in the literature. We argue that an effective way to rule out kHz QPO models is to observationally find such high Q-factors, even for a short duration, as many models cannot explain a high coherence. However, as we demonstrate, the shift-and-add technique cannot find a very high Q-factor which appears for a short period of time. This shows that the coherences of kHz QPOs can be higher than the already high values reported using this technique, implying further constraints on models. We also discuss the energy dependence of fractional rms amplitude and Q-factor of the kHz QPO.

Subject headings: accretion, accretion disks — stars: individual: EXO 1745–248 — stars: neutron — X-rays: binaries — X-rays: individual: EXO 1745–248 — X-rays: stars

1. INTRODUCTION

Many neutron star low mass X-ray binary (LMXB) systems show high frequency ($\sim 200 - 1200$ Hz) and somewhat coherent intensity variations (van der Klis 2006; Bhattacharyya 2010). Such variations are known as kilohertz quasi-periodic oscillations (kHz QPOs). Sometimes these QPOs appear in a pair; the higher frequency one is called the upper kHz QPO, while the lower frequency one is known as the lower kHz QPO. Soon after their discovery (van der Klis et al. 1996; Strohmayer et al. 1996), it was realized that they originate from within a few Schwarzschild radii of the neutron star, and hence could be useful to probe the strong gravity regime, as well as the supranuclear degenerate matter of the stellar core. Despite this potential, so far kHz QPOs could not be used as a reliable tool, because their correct theoretical model has not been identified yet. Many proposed models of this timing feature primarily attempt to explain the frequency (e.g., Miller et al. (1998); Stella and Vietri (1998, 1999); Lamb and Miller (2003); Kluźniak and Abramowicz (2001); Abramowicz and Kluźniak (2001); Wijnands et al. (2003); Lee et al. (2004); Zhang (2004); Mukhopadhyay (2009)). Some of these models involve various general relativistic frequencies at preferred radii and the neutron star spin frequency. Such models can have good predictive power (Bhattacharyya 2010). However, it is not enough to explain only the frequency in order to understand the kHz QPOs. The modulation mechanism (how the intensity actually varies) and the decoherence mechanism (why the QPOs are not very narrow) are also required to be understood.

Méndez (2006) proposed that, although the kHz QPO frequencies are plausibly determined by the characteristic disk frequencies, the modulation mechanism is likely associated to the high energy spectral component (e.g., ac-

cretion disk corona, boundary layer, etc.). This is because the disk alone cannot explain the large observed amplitudes, especially at hard X-rays where the contribution of the disk is small. Moreover, the kHz QPO fractional amplitude increases with energy, and plausibly reaches a saturation value (e.g., Gilfanov et al. (2003)). Therefore, an accurate measurement of the amplitude vs. energy curve might be useful to understand the modulation mechanism.

The lack of coherence (aperiodicity) of kHz QPOs could be intrinsic (e.g., shot-noise models; van der Klis (2006) and references therein), or might be because of a decoherence mechanism or frequency drift. The decoherence could be because of a damped harmonic oscillator or a finite lifetime of a clump of matter. A timing feature originating from a finite-width disk annulus could also be broadened because of the superposition of a range of frequencies. A frequency drift, for example due to a varied preferred disk radius, might also broaden the feature. Elimination of the effects of frequency superposition and drift is required to measure the coherence of the underlying signal, which is essential to understand the kHz QPOs. The shift-and-add technique of Méndez et al. (1998), which was originally used to discover an upper kHz QPO from 4U 1608–52, has been used by several authors (Barret et al. 2005a,b, 2006, 2010) to track the frequency drift. Subsequent alignment of kHz QPOs in smaller time segments make the signal much more prominent, and allows one to measure its quality (Q) factor or coherence. The Q-factor is the ratio of the QPO centroid frequency to the full-width half maximum (FWHM) of the QPO profile. Barret et al. (2005a,b, 2006) noticed that, while the Q-factor of lower kHz QPOs can be up to ~ 200 , that of upper kHz QPOs is always less than 50. These authors have also found that the Q-factor of the lower kHz QPO first increases with frequency, and then after a frequency characteristic

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of a source, the Q-factor decreases. They tentatively interpreted this as a signature of the innermost stable circular orbit (ISCO; but see Méndez (2006)), whose existence is a key prediction of strong field general relativity. Note, however, although the shift-and-add technique tracks the frequency drift correctly, it gives an average Q-factor value over a long period. Consequently, this technique would miss a plausible very high Q-factor value, if such a value appears for a short period of time.

In this Letter, we report the discovery of a very strong lower kHz QPO from the neutron star LMXB EXO 1745-248, and a very high coherence of this QPO for a short duration.

2. DATA ANALYSIS AND RESULTS

The globular cluster Terzan 5 contains several point X-ray sources (Heinke et al. 2006). Among them the transient neutron star LMXB EXO 1745-248 went into outburst in 2000 and 2002. These outbursts were observed with *Rossi X-ray Timing Explorer (RXTE)* between Jul 13 (start time: 13:27:50) and Nov 3 (end time: 00:17:52) in 2000, and between Jul 2 (start time: 20:38:24) to Jul 22 (end time: 19:42:08) in 2002. The total observation time was ≈ 144 ks (proposal nos. P50054, P50138, P70412). We have searched for kHz QPOs in the corresponding science event mode (resolution $122 \mu\text{s}$) Proportional Counter Array (PCA) data. In order to do this, we have created one power spectrum from each segment of continuous observation considering all the PCA channels. Note that an ObsID may contain more than one segment, and we have removed bursts and data gaps before doing the Fourier transform. In order to identify a burst, we have calculated average count rate in each 10 s bin in a segment. We have considered that a bin has a burst, if the count rate of that bin is more than 3.2 times that of the previous bin. We have then excluded from 10 s before that bin up to 180 s after that bin. Using rest of the data, we have performed Fourier transform on each 10 s bin, and then averaged all the Leahy normalized power spectra (van der Klis 1989) within one segment. From the entire data set, we have created 146 averaged Leahy power spectra (each from one segment) with resolution and Nyquist frequency of 0.1 Hz and 2048 Hz respectively. A prominent peak at 691 ± 25.6 Hz has been observed in the Leahy power spectrum of the PCA data of Sep 30, 2000 (15:29:24 to 16:24:09; obsId: 50054-06-11-00; see Fig. 1). With a frequency resolution of 51.2 Hz, the peak power ≈ 2.103 , implying a single trial significance of $\approx 1 - 2.68 \times 10^{-95}$ for 326 time bins of 10 s (van der Klis 1989). A conservative number of trials (N_{trial}) can be calculated from the original number (20480) of powers in a power spectrum multiplied with the total number (146) of averaged Leahy power spectra searched. With this N_{trial} value, a kHz QPO can be considered to be detected with a significance of $\approx 1 - 8.01 \times 10^{-89}$, i.e., $\approx 20\sigma$. We have then fitted the power spectrum with a constant+powerlaw+Lorentzian model, taking care of Poissonian noise, red noise and the candidate peak, respectively, which gives an acceptable χ^2_{ν} (dof) = 0.89 (33). The Lorentzian describes the kHz QPO, and gives its centroid frequency ($\nu_{\text{QPO}} = 686.8 \pm 0.9$ Hz), FWHM (28.3 ± 2.5 Hz), Q-factor (24.3 ± 2.2) and background corrected fractional rms amplitude ($9.6 \pm 0.3\%$). The fractional rms amplitude has been calculated using the integrated power in the

Lorentzian component and the standard technique mentioned in van der Klis (1989). The background subtraction has been done using the equation 1 of Muno et al. (2002).

The very significant kHz QPO is broad and it has sub-features, as mentioned in our Astronomer's Telegram (Mukherjee and Bhattacharyya 2010). We have investigated whether the width of the QPO is a result of decoherence, or caused by the frequency drift. In order to do this, we have divided the data segment into two equal parts of 1630 seconds, and created an average power spectrum for each of them using the same procedure mentioned earlier. Now the question is whether the frequencies of the kHz QPOs (if detected) of the two power spectra are significantly different from each other. First we need to set a detection criterion. We have considered an $N_{\text{trial}} = \text{searched frequency range divided by frequency resolution} = 200/0.1 = 2000$, because (1) the kHz QPO of the entire segment is already established, and (2) we have searched for the kHz QPO in the half segments within 100 Hz on each side of ν_{QPO} . Then a kHz QPO from a half segment is considered to be detected if the product of N_{trial} and the single trial significance is better than 3σ with a frequency resolution of 0.4 Hz or better. The kHz QPOs of both the half segments have been detected, since the single trial significances are $\approx 6.70 \times 10^{-32}$ and $\approx 2.85 \times 10^{-38}$. The best-fit centroid frequency, FWHM, Q-factor and fractional rms amplitude of the kHz QPOs of first and second half segments are 704.0 ± 0.9 Hz, 23.7 ± 2.5 Hz, 29.7 ± 3.2 and $10.0 \pm 0.3\%$, and 680.2 ± 0.3 Hz, 11.5 ± 1.0 Hz, 59.1 ± 4.9 and $9.4 \pm 0.3\%$ respectively. Therefore, the Q-factor has increased from that for the entire segment. Moreover, the significant frequency difference between the two half segments shows that the structure and the large width of the kHz QPO exhibited in Fig. 1 were caused by frequency drift.

This has motivated us to further divide the data segment in order to check if a higher Q-factor could be obtained. We have created power spectra using the above mentioned procedure for quarter segments, one-eighth segments and one-sixteenth segments. It is difficult to detect the kHz QPO for any one-thirtysecond segment. The above mentioned criterion allows us to detect kHz QPO in six one-eighth segments and six one-sixteenth segments. Fig. 2 displays that the kHz QPO frequency shifts from one quarter segment to another. Fig. 3 shows that the Q-factor increases for smaller time segments. The highest Q-factor (264.5 ± 38.5) we have obtained is for the sixth one-sixteenth segment (Fig. 3). The single trial significance of the kHz QPO of this segment is $\approx 9.16 \times 10^{-8}$, which shows that it is somewhat strong (panel *a* of Fig. 4).

Next, we have checked the effect of the shift-and-add technique (see § 1) on the narrow kHz QPO features. Panel *b* of Fig. 4 shows the average power spectrum from the six one-sixteenth segments with the kHz QPOs aligned at ν_{QPO} . As expected, the shift-and-add technique makes the kHz QPO more prominent, but with a Q-factor (155.5 ± 10.3) much smaller than the highest Q-factor (264.5 ± 38.5) obtained for an individual segment.

Finally, we have plotted the background corrected fractional rms amplitude vs. energy and Q-factor vs. energy of the kHz QPO for the entire segment. (Fig. 5). The rms

clearly increases with energy. An F-test (null hypothesis probability ≈ 0.01) between a constant model and a linear model indicates a plausible increase of Q-factor with energy.

3. DISCUSSION

In this Letter, we report the first detection and analysis of a kHz QPO from the neutron star LMXB EXO 1745–248. In order to investigate if its apparent large width and structure are caused by the frequency drift, we have divided the data segment into smaller parts (see § 2). Note that initially we have not used the shift-and-add technique, so that the Q-factor of the underlying signal does not get averaged, and we can study its time variation within a short duration. The measured $Q > 50$ values for all the smaller parts except one (Fig. 3) show that this is a lower kHz QPO (§ 1). We have not found an upper kHz QPO even by the shift-and-add technique (§ 2). The frequency of the QPO roughly monotonically drifts by ~ 30 Hz in about an hour (Fig. 2). The variations of fractional rms amplitude (8 – 10%) and Q-factor, however, are not correlated with the frequency change in our limited time and frequency ranges.

The fact that the Q-factor is generally larger for smaller time segments, and the frequency shifts from one segment to another shows that the frequency drift plays a major role in broadening the QPO. At the level of one-sixteenth segment (200 s; § 2), the width of the QPO may still be caused by the combined effect of a small frequency drift, the superposition of a small frequency range, and a decoherence mechanism. Since we cannot divide the time segment any further (see § 2), our estimated Q-factor is only a lower limit. The corresponding lower limit of the coherence time τ can be calculated from $\tau = 1/(\pi \times \text{FWHM})$, where the QPO profile is fitted with a Lorentzian, and we assume that the signal consists of exponentially damped sinusoidal oscillator (Barret et al. 2005a; van der Klis 2006).

For a one-sixteenth segment we have measured a Q-

factor of 264.5 ± 38.5 , which might be the largest value reported in the literature (Barret et al. (2005b) reported $Q = 222 \pm 24$ for 4U 1636–536). Moreover, this value appears at ≈ 694 Hz. From Barret et al. (2006) we find that Q-factor near this frequency is found to be less than 150. The minimum τ corresponding to a Q-factor of 264.5 is 0.12 s. Many models will find it difficult to explain such a large τ (see Barret et al. (2005a) for a discussion). For example, kHz QPO models based on accretion flow inhomogeneities in the form of clumps should have $\tau \lesssim 0.01$ s (Barret et al. 2005a). Therefore, an effective way to constrain and rule out kHz QPO models is to observationally find high Q-factors, even for a short duration. If the Q-factor considerably varies within short ranges of time and frequency (see Fig. 3), the shift-and-add technique (§ 1), which gives an average Q-factor and QPO structure, cannot find such high Q-factors. We have demonstrated this in Fig. 4 (§ 2). Therefore, while the Q-factor vs. frequency trend reported by Barret and coauthors should be useful to probe fundamental physics, the Q-factor of lower kHz QPOs can be much larger at times than the reported peak values of these authors.

Finally, the observed increase of fractional rms amplitude with energy is common for kHz QPOs (e.g., Gilfanov et al. (2003)), and may provide crucial information about the hard X-ray modulation mechanism by identifying a modulation site (see § 1). Moreover, a plausible increase of Q-factor with energy indicates that oscillations from harder X-ray components are more coherent than those from softer X-ray components. *Astrosat* with its sufficient time resolution and an area larger than *RXTE* PCA at hard X-rays might be ideal to probe these trends.

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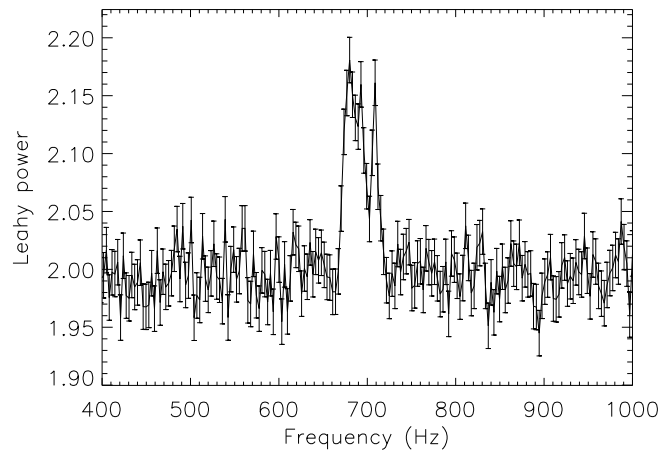


FIG. 1.— Power spectrum with frequency resolution of 3.2 Hz from *RXTE* PCA data (Sep 30, 2000: 15:29:24 to 16:24:09) of the neutron star LMXB EXO 1745–248. A kHz QPO at ~ 690 Hz with $\approx 20\sigma$ significance is clearly seen (§ 2).

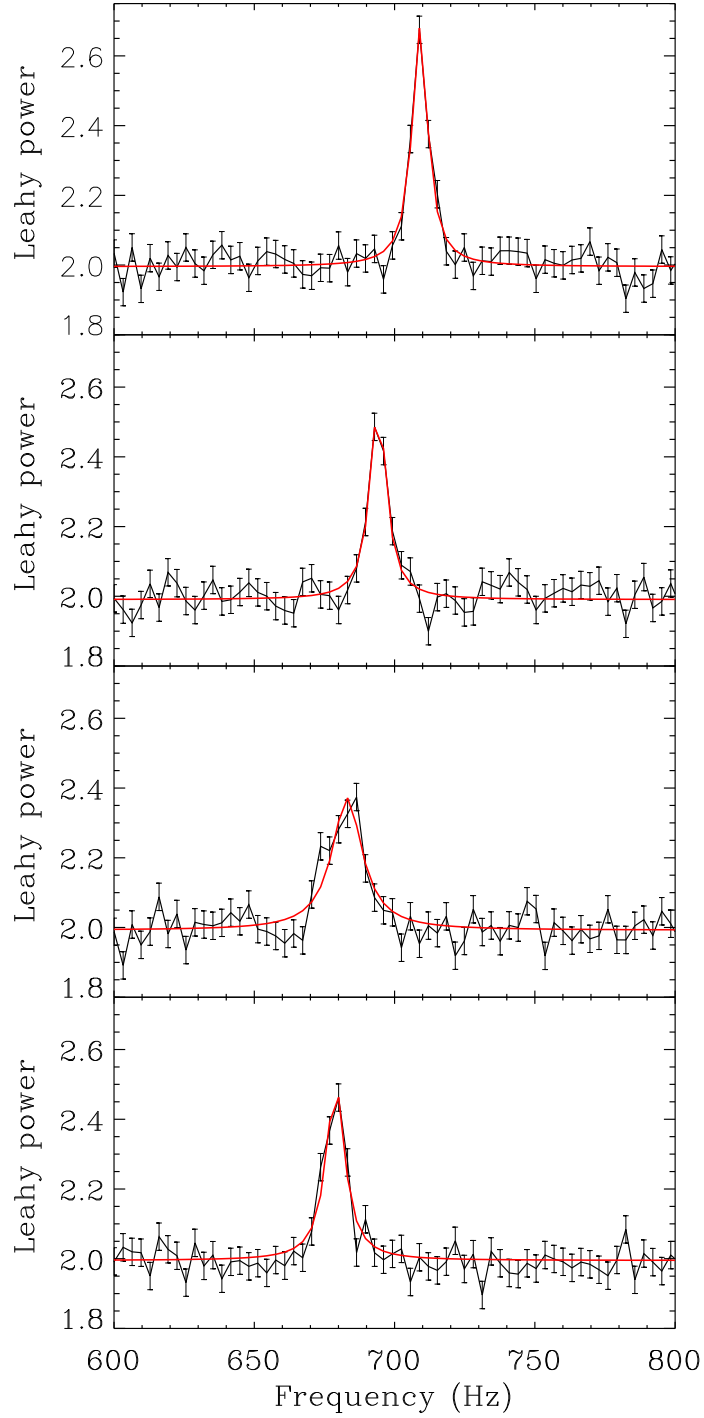


FIG. 2.— Power spectra of quarter segments (810 s each; chronologically from top panel to bottom panel) of the data set containing the kHz QPO (§ 2). The data points with 1σ error bars, and the “constant+powerlaw+Lorentzian” model are displayed. This figure shows that the kHz QPO is very significant in each quarter segment, and the centroid frequency monotonically decreases with time.

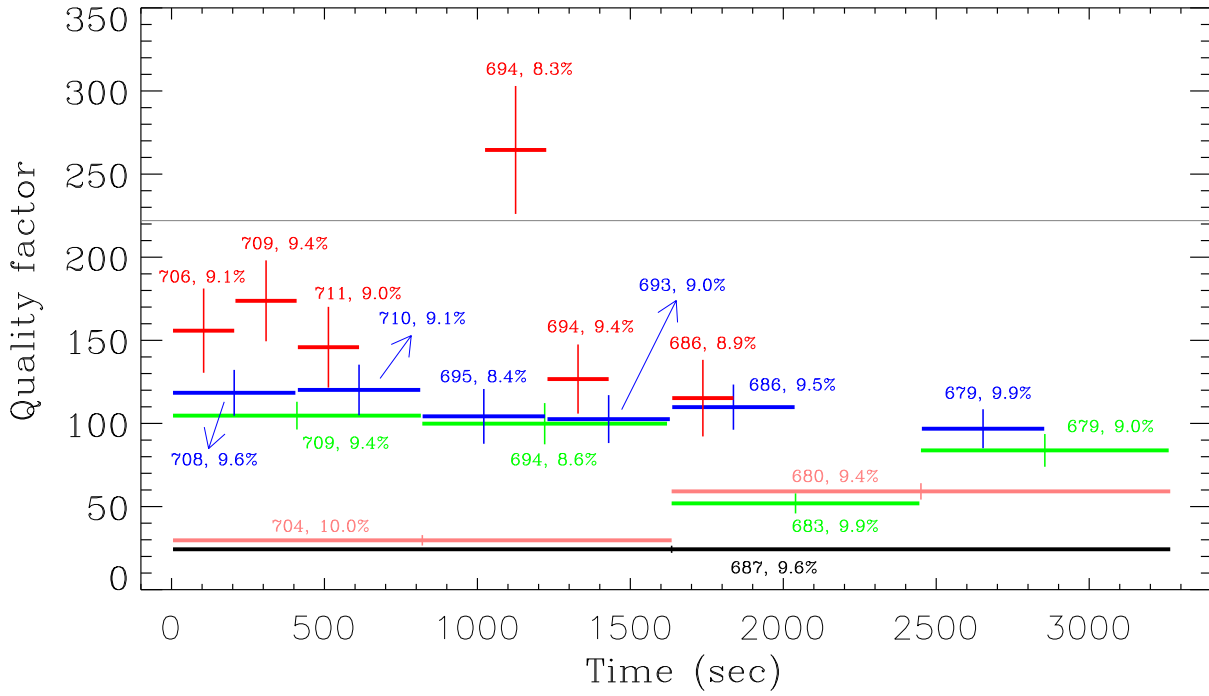


FIG. 3.— Time variation of Q-factor of the kHz QPO from EXO 1745-248 using time segments of various lengths (§ 2). Each horizontal line, with approximate kHz QPO centroid frequency and rms amplitude written next to it, gives the time span for which the Q-factor is measured. The corresponding vertical line gives the 1σ error of the Q-factor. The light horizontal line gives the plausibly highest Q-factor value (222) previously reported (§ 3). This figure shows a greater Q-factor (264.5), and a significant change in Q-factor at almost the same frequency.

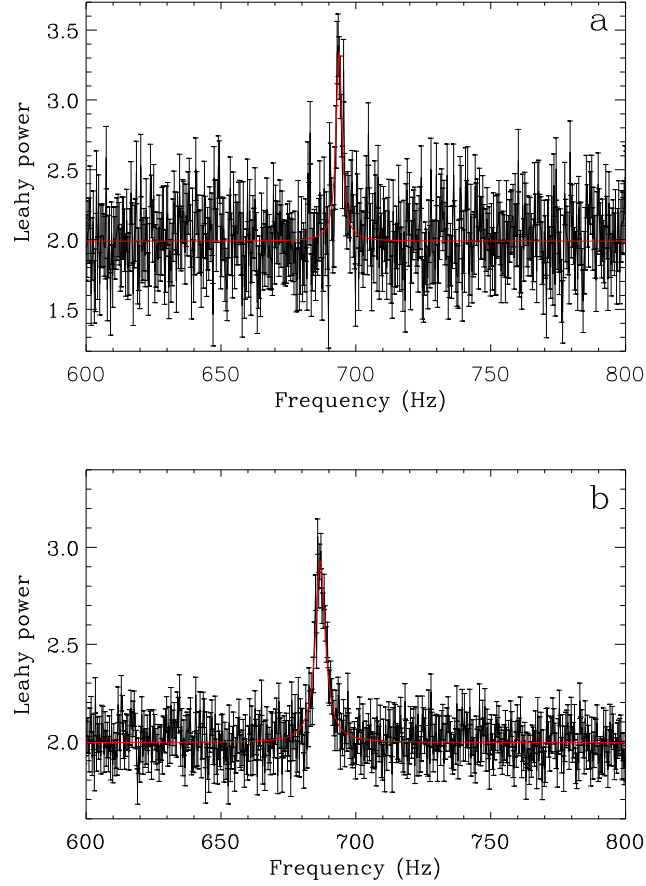


FIG. 4.— Power spectra of the data set from EXO 1745–248 containing the kHz QPO. Each panel shows the data points with 1σ error bars, and the “constant+powerlaw+Lorentzian” model. Panel *a*: shows the kHz QPO of the one-sixteenth segment with a Q-factor of 264.5 ± 38.5 (see Fig 3 and § 2). Panel *b*: shows the kHz QPO after applying the shift-and-add technique to six one-sixteenth segments (§ 2). This figure shows that while the shift-and-add technique makes the QPO more prominent, the measured coherence from this technique can be much lower than the highest coherence obtained from an individual segment.

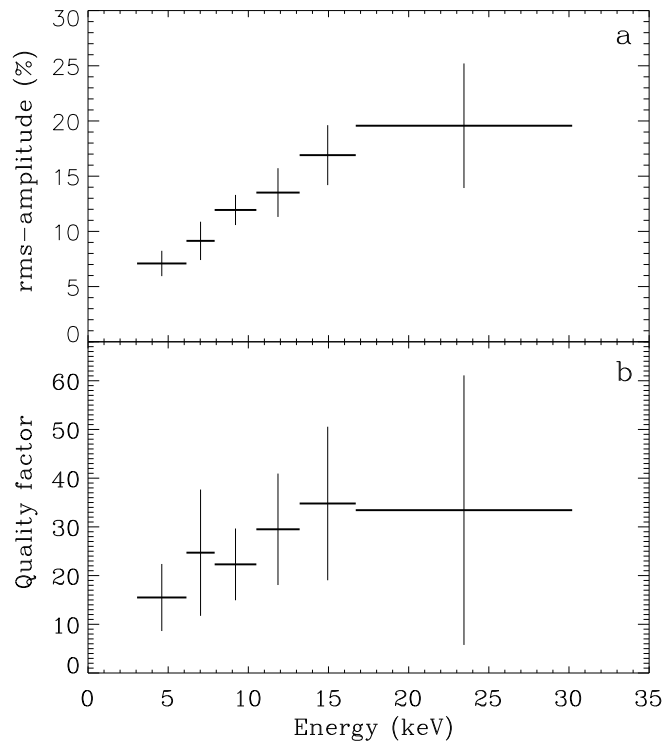


FIG. 5.— Properties of the kHz QPO from EXO 1745–248. Panel *a*: shows that the background corrected fractional rms amplitude increases with energy. Panel *b*: shows a weak trend of Q-factor increase with energy.